

# **Carbothermal Reduction of Magnesia in a Reduced Pressure Hybrid Solar-Electric Reactor**

**University of Colorado  
at Boulder**

**August 24 – 25, 2016**

**Detroit, MI**

**METALS Annual Meeting**



# Meet the Core Team



Alan  
Weimer

**PI**



Aaron  
Palumbo

**Post-doc**



Scott  
Rowe

**GRA**



Boris  
Chubukov

**GRA**



Mark  
Wallace

**PRA**



Chip  
Fisher

**PRA**

Ronggui Yang, Prof.  
David Clough, Prof.  
Eben Johnson, Prof.  
Ray Johnson, Instructor

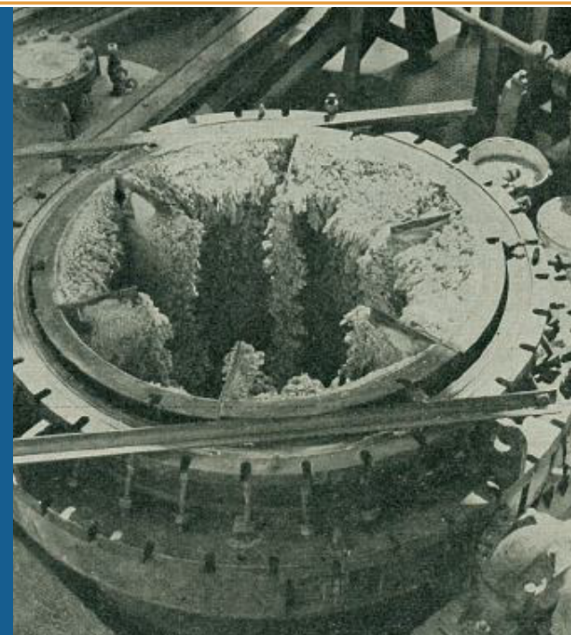
Arto Groehn, Post-doc  
Illias Hischier, Post-doc  
David Geb, Post-doc  
Allan Lewandowski, Consultant

# The Appeal of Carbothermal Magnesium



Konan, Korea  
ca. 1938

Permanente, CA  
ca. 1941



[t=metric ton]	Carbon	Ferrosilicon*
Amount Required for Mg Production (kg/t-Mg)	750	1,010
Delivered Cost (\$/t)	\$150 – 350	\$1,190
Operating Cost (\$/t-Mg)	\$110 - 260	\$1,200

# The **Problem** of Carbothermal Magnesium



Konan, Korea  
ca. 1938

Permanente, CA  
ca. 1941



Low  
~ 50%  
Yield

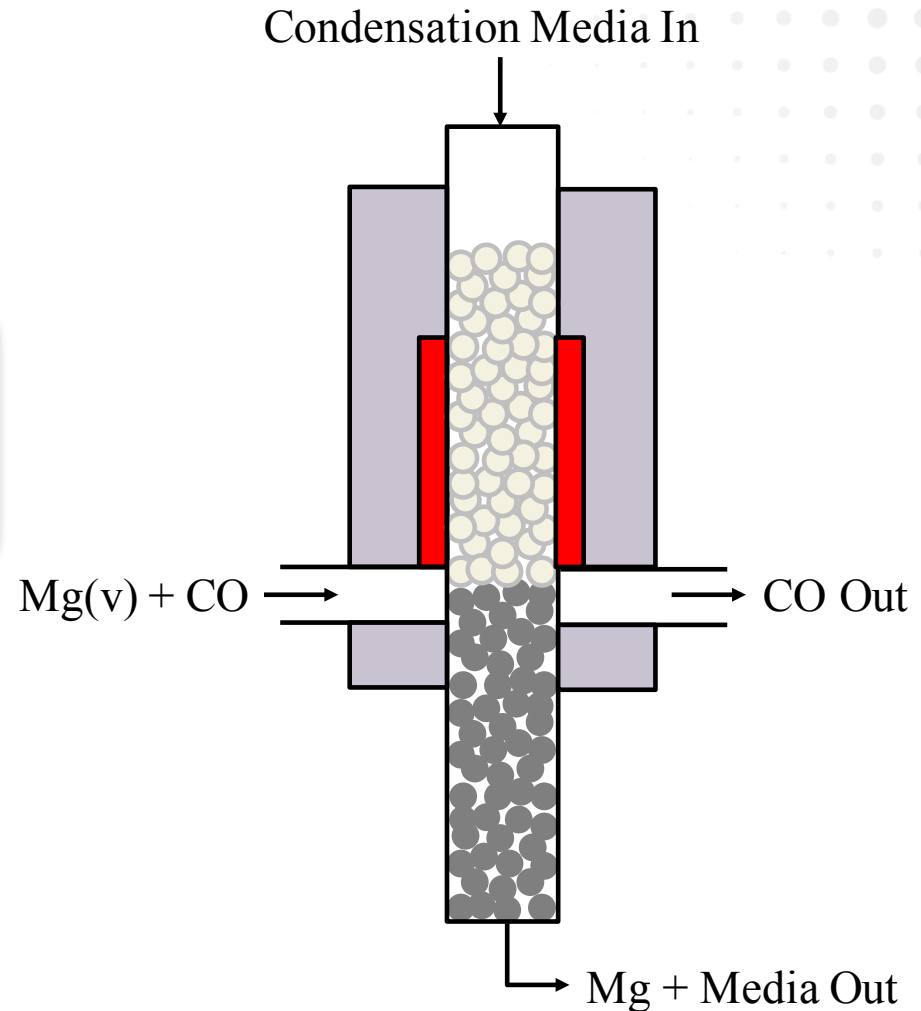
CO Byproduct  
Re-oxidizes  
Mg Product



# Project Scope



1. Carbothermal reduction of MgO in a moving bed (**forward reaction**)
2. Continuous deposition of metallic Mg onto a moving bed of media (**reverse reaction**)
3. Use hybridized **solar & electric** energy for heat inputs
4. Apply **CFD & Model Predictive Control**

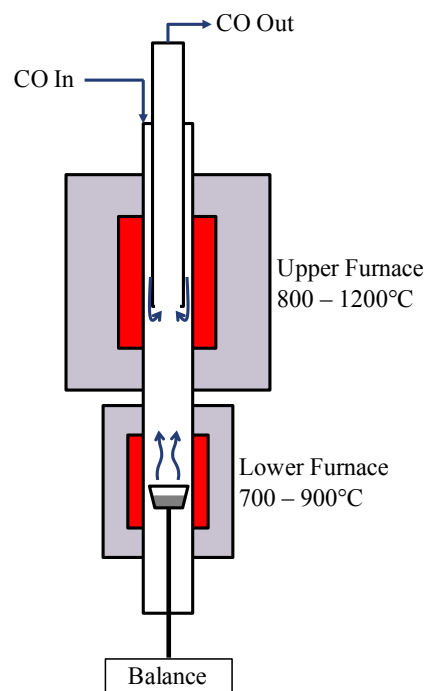


# Non-Solar Experimental Test Systems



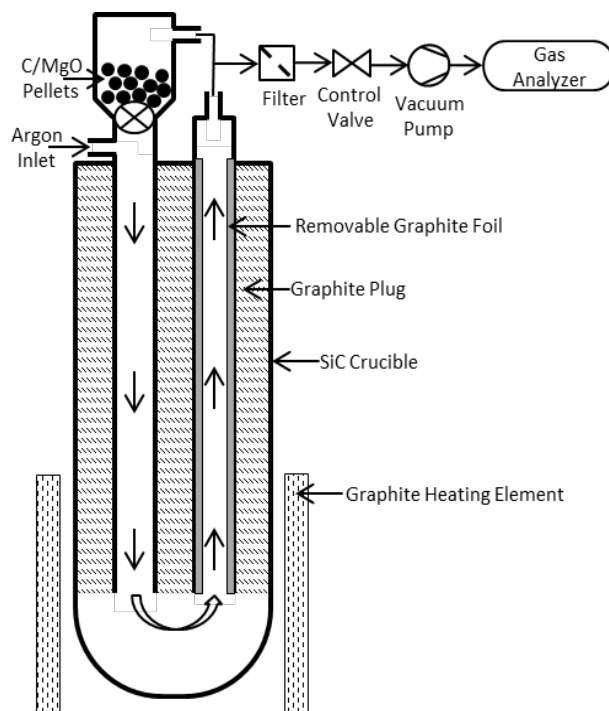
## SYSTEM 1

Reverse Reaction &  
Mg Condensation  
Behavior<sup>a</sup>



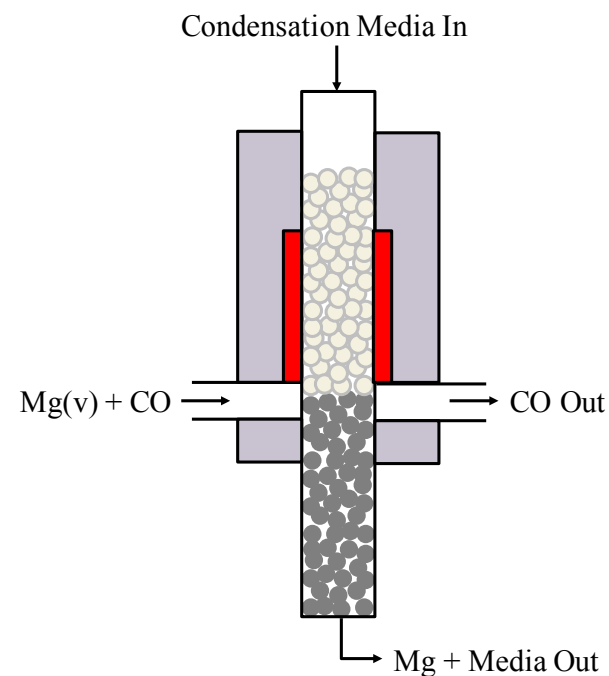
## SYSTEM 2

Forward Reaction &  
Chemical Reaction  
Engineering<sup>b</sup>



## SYSTEM 3

Moving Bed Condensation  
Proof of Concept<sup>c</sup>



# Solar Tasks in Progress



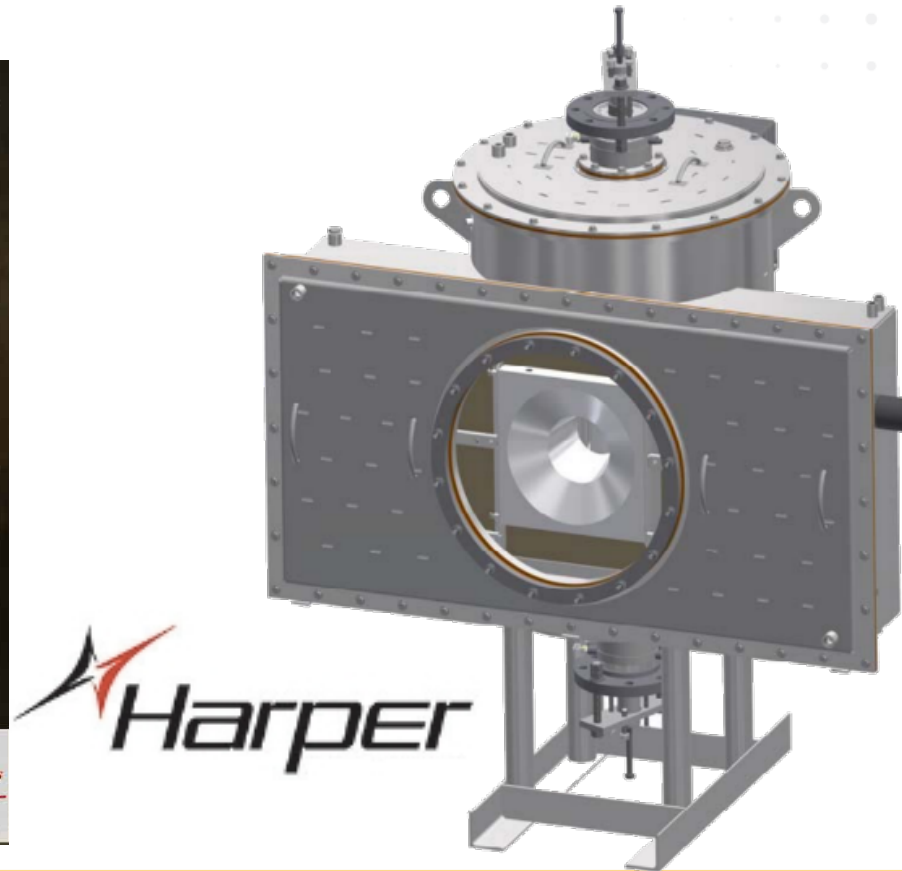
## SYSTEM 4

45kW<sub>e</sub>, 18-lamp High Flux Solar Simulator<sup>a</sup>  
5-axis filament positioning system



## SYSTEM 5

10 kW<sub>th</sub> Solar-Electric Reactor<sup>b</sup>

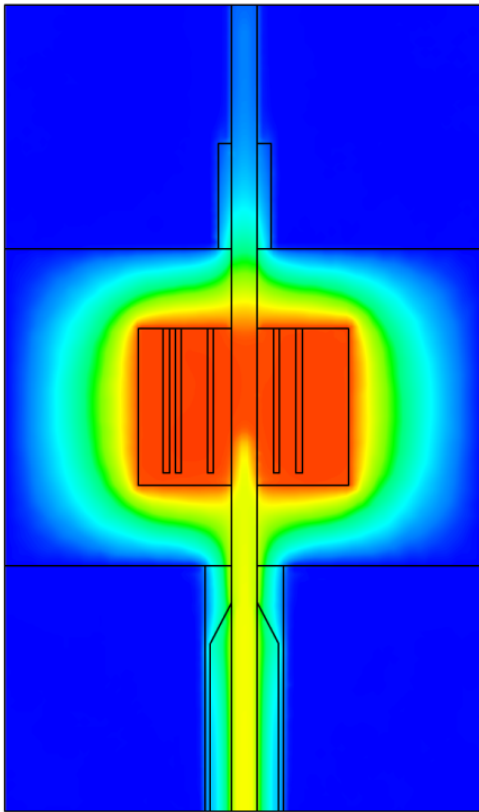


# Modeling and Model Predictive Control

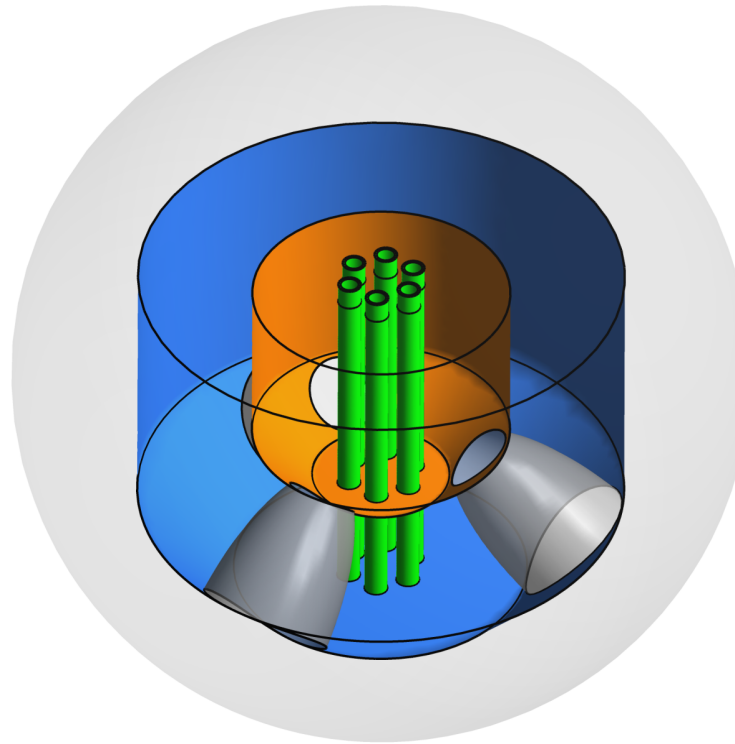


## CFD Modeling<sup>a</sup>

Actual solar-electric reactor

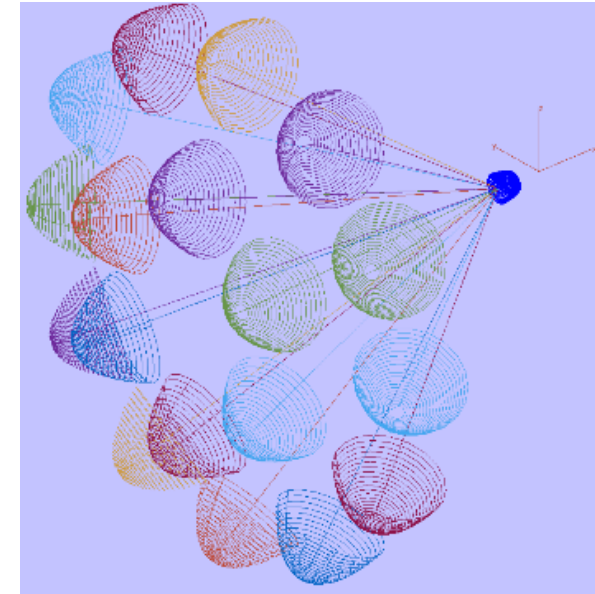


Commercial multi-tube reactor



## CUtrace<sup>b</sup>

Open-source ray tracing software





# Status – Highlights



Publications/Patents

8

Accepted/Submitted

Reproducible

85%

Mg Yield

Letter of Intent

1

To Purchase Mg

Experimental

7

Systems

Continuous Prototype

10

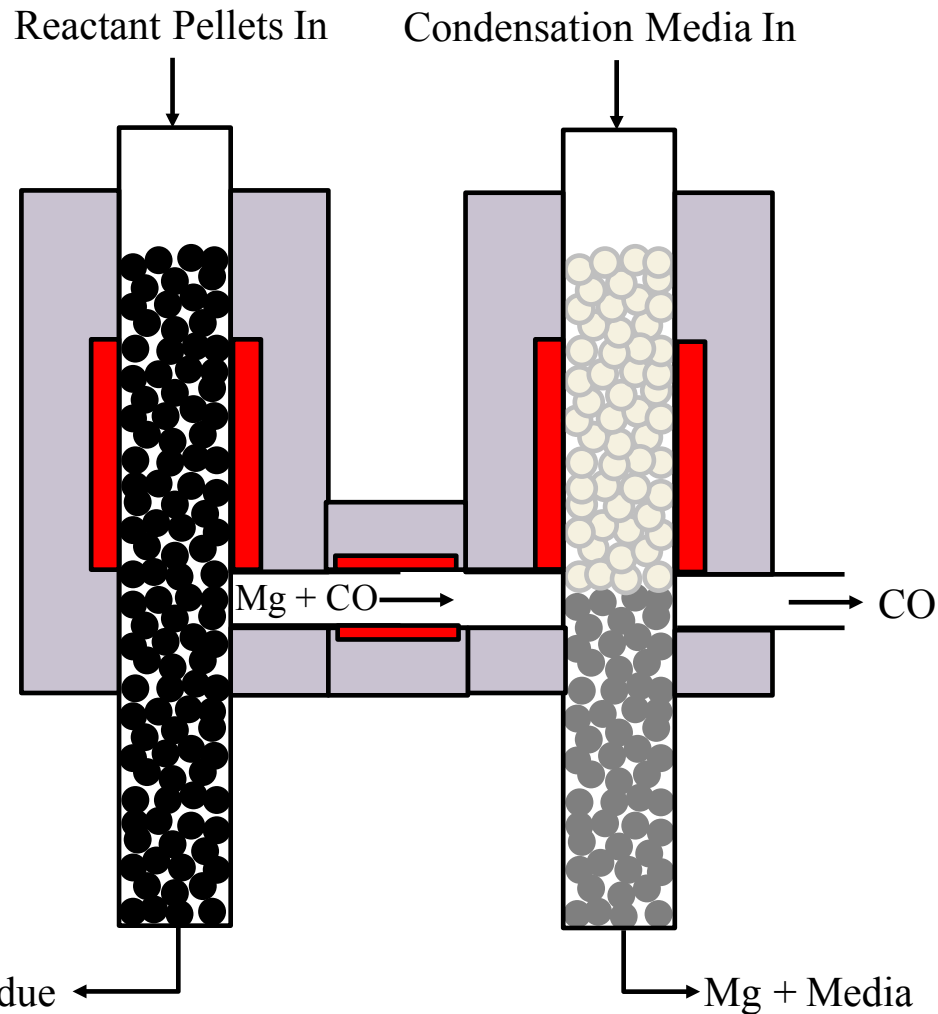
g/hr

Follow-On

\$236k

Funding

# Current Work: Integration (Electric Only)



## Targets

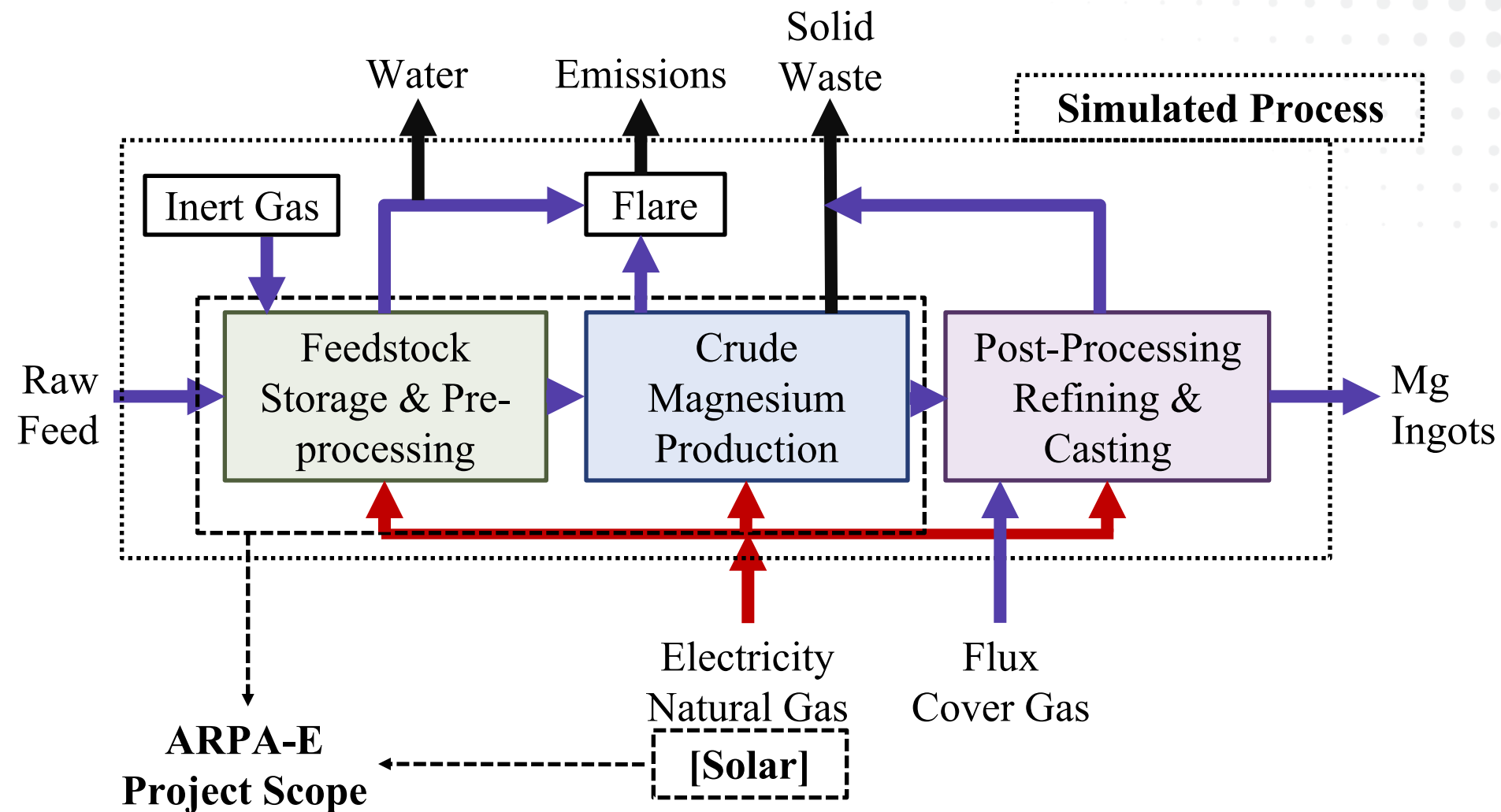
100 g/hr

+80% Mg Yield

1 kg collected

+90% Conversion  
in < 30 minutes

# Simplified Process Boundaries



# Process Energy & Emissions



Brucite Ore (Base Case)	Electricity [kWh/kg-Mg]	Natural Gas [kWh/kg-Mg]	CO <sub>2</sub> Emissions [kgCO <sub>2</sub> /kg-Mg]
Pre-Processing	1.0	2.2	0.6
Mg Production	10.4 [6.9]	3.3	4.4 [3.2]
Post-Processing	0.8	9.8	2.0
<i><b>SUBTOTAL</b></i>	<b>12.4 [8.7]</b>	<b>15.3</b>	<b>7.0 [5.8]</b>
Process Gas Flare			2.0
<i><b>TOTAL</b></i>	<b>27.5 [24.0]</b>		<b>9.0 [7.8]</b>

[Concentrated solarthermal energy  
assumed at 8 hours per day]



# Competitive Analysis



Carbothermic and silicothermic methods are analogous thermochemical routes to Mg

## CU-Boulder

Reductant = Carbon

< \$ 1,600

30 MWh

15 t-CO<sub>2</sub>

\$4,000

COGS

Energy

Emissions

Capital Intensity

## Pidgeon, etc.

Reductant = (Ferro)Silicon

\$1,500-1,900

80-100 MWh

25-40 t-CO<sub>2</sub>

\$3,200

# Introducing Big Blue Technologies LLC



Analytical/Experimental



Services



Excl.  
License



# Next Steps: Partnerships & Scale-Up



## Design & Build Pilot System

Demonstrate core innovation steps at 10 kg/hr

## Find Partners

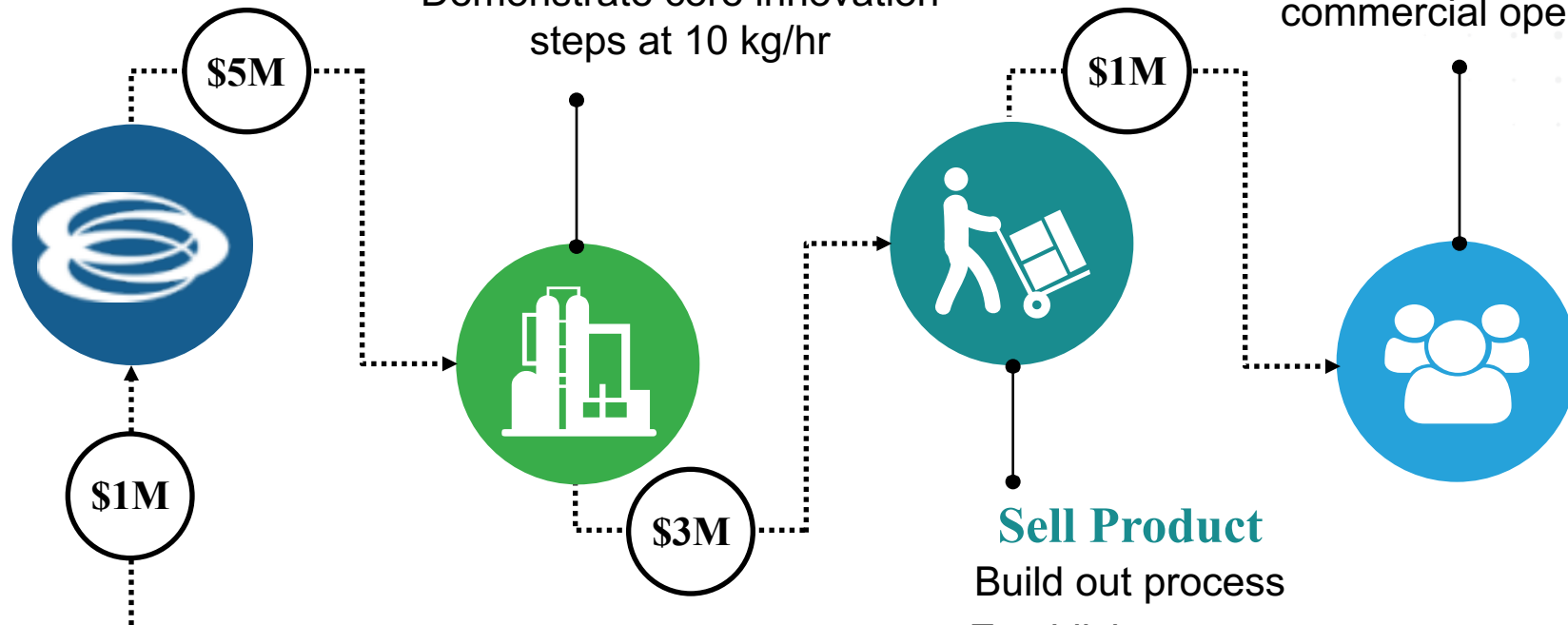
Transition to commercial operations

## Sell Product

Build out process  
Establish revenue  
Plan commercial facility

## Low-Capital Scale-Up

In collaboration with **Garrison Minerals**, use existing equipment for 1 kg-Mg/hr



# Moving Forward with Development



Ask:  
LoS

\$2M  
Leveraged Grant  
Funding Available

Source	Grant	Match	Deadline
✓ NSF STTR Phase I	\$225k	\$0	Jul 2016
Colorado AIA: PoC	\$150k	\$50k	Nov 2016
NSF SBIR Phase II	\$750k	\$0	Feb 2017
Colorado AIA: Early Capital	\$250k	\$500k	Dec 2017
<b>TOTAL</b>	<b>\$1.38M</b>	<b>\$0.55M</b>	





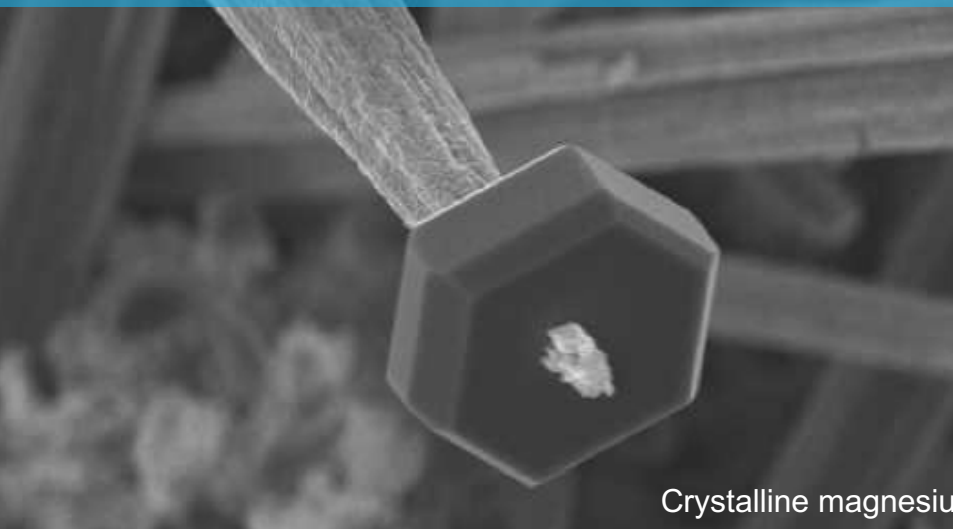
University of Colorado  
Boulder



Big Blue Technologies  
*Toward a lighter future*

Alan Weimer  
alan.weimer@colorado.edu

Aaron Palumbo  
palumbo@bigbluetec.com



Crystalline magnesium pins and hexagons